

## Nucleosynthesis around black holes

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**Abstract.** Study of nucleosynthesis in accretion disks around black holes was initiated by Chakrabarti et al. (1987). In the present work we do the similar analysis using the state-of-the-art disk model, namely, Advective Accretion Disks. During the infall, matter temperature and density are generally increased which are first computed. These quantities are used to obtain local changes in composition, amount of nuclear energy released or absorbed, etc. under various inflow conditions. In the cases where the magnetic viscosity is dominant neutron torus may be formed. We also talk about the fate of  $Li^7$  and  $D$  during the accretion. The outflowing winds from the disk could carry the new isotopes produced by nucleosynthesis and contaminate the surroundings. From the degree of contamination, one could pinpoint the inflow parameters.

**Keywords :** Accretion, black holes, nuclear astrophysics, origin and abundance of elements

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### 1. Introduction

There are many observational evidences where the incoming matter has the potential to become as hot as its virial temperature  $T_{\text{virial}} \sim 10^{13} \text{ K}$  [1]. Through various cooling effects, this incoming matter is usually cooled down to produce hard and soft states [2]. In the accretion disk, matter in the sub-Keplerian region generally remains hotter than Keplerian disks. The matter is so hot that after big-bang nucleosynthesis this is the most favourable temperature to produce significant nuclear reactions. The energy generation due to nucleosynthesis could be high enough to destabilize the flow and the modified composition may come out through winds to affect the metallicity of the galaxy [3-7]. Previous works on nucleosynthesis in disk was done for cooler

thick accretion disks. Since the sub-Keplerian region is much hotter than of Keplerian region and also than the central temperature ( $\sim 10^7\text{K}$ ) of stars, presently we are interested to study nucleosynthesis in hot sub-Keplerian region of accretion disks.

## 2. Basic equations and physical systems

In 1981 Paczyński & Bisnovatyi-Kogan [8] initiated the study of viscous transonic flow although the global solutions of advective accretion disks were obtained much later [9] which we use here. In the advective disks, matter must have radial motion which is transonic. The supersonic flow must be sub-Keplerian and therefore must deviate from a Keplerian disk away from the black hole. The basic equations which matter obeys while falling towards the black hole from the boundary between Keplerian and sub-Keplerian region are given below (for details, see, [9]):

(a) The radial momentum equation:

$$\vartheta \frac{d\vartheta}{dx} + \frac{1}{\rho} \frac{dP}{dx} + \frac{\lambda_{Kep}^2 - \lambda^2}{x^3} = 0, \quad (1a)$$

(b) The continuity equation:

$$\frac{d}{dx}(\Sigma x \vartheta) = 0, \quad (1b)$$

(c) The azimuthal momentum equation:

$$\vartheta \frac{d\lambda(x)}{dx} - \frac{1}{\Sigma x} \frac{d}{dx}(x^2 W_{x\phi}) = 0, \quad (1c)$$

(d) The entropy equation:

$$\frac{2na\rho\vartheta h(x)}{\gamma} \frac{da}{dx} - \frac{a^2\vartheta h(x)}{\gamma} \frac{d\rho}{dx} = fQ^+ \quad (1d)$$

where the equation of state is chosen as  $a^2 = \frac{\gamma P}{\rho}$ . Here,  $\lambda$  is the specific angular momentum of the infalling matter,  $\lambda_{Kep}$  is that in the Keplerian region is defined as  $\lambda_{Kep}^2 = \frac{x^3}{2(x-1)^2}$  [10],  $\Sigma$  is vertically integrated density,  $W_{x\phi}$  is the stress tensor,  $a$  is the sound speed and  $h(x)$  is the half thickness of the disk ( $\sim ax^{1/2}(x-1)$ ),  $n = \frac{1}{\gamma-1}$  is the polytropic index,  $f$  is the cooling factor which is kept constant throughout our study,  $Q^+$  is the heat generation due to the viscous effect of the disk. For the time being we are neglecting the magnetic heating term.

During infall different nuclear reactions take place and nuclear energy is released. Here, our study is exploratory so in the heating term  $Q^+$ , we do not include the heating due to nuclear reactions. (Work including nuclear energy

release term is in [6].) Another parameter  $\beta$  is defined as ratio of gas pressure to total pressure, which is assumed to be a constant value throughout a particular case. Actually, the factor  $\beta$  is used to take into account the cooling due to Comptonization. To compute the temperature of the Comptonized flow in the advective region which may or may not have shocks, we follow Chakrabarti & Titarchuk [2] and Chakrabarti's [11] works and method. The temperature is computed from.

$$T = \frac{a^2 \mu m_p \beta}{\gamma k}. \quad (2)$$

It is seen that due to hotter nature of the advective disk especially when accretion rate is low, Compton cooling is negligible, the major precess of hydrogen burning is the rapid proton capture process, which operates at  $T \gtrsim 0.5 \times 10^9 \text{K}$  which is much higher than the operating temperature of PP chain (operates at  $T \sim 0.01 - 0.2 \times 10^9 \text{K}$ ) and CNO cycle (operates at  $T \sim 0.02 - 0.5 \times 10^9 \text{K}$ ) which take place in the case of stellar nucleosynthesis where temperature is much lower. Also in stellar case, in different radii same sets of reaction take place but in the case of disk, in different radii different reactions (or different sets of reaction) can take place simultaneously. These are the basic differences between the nucleosynthesis in stars and disks.

For simplicity, we take the solar abundance as the initial abundance of the disk and our computation starts where matter leaves a Keplerian disk. According to [2] and [11], the black hole remains in hard states when viscosity and accretion rate are smaller. In this case,  $x_K$  (at radius  $x_K$  matter deviates from Keplerian to sub-Keplerian region) is large. In this parameter range the protons remain hot ( $T_p \sim 1 - 10 \times 10^9 \text{K}$ ). The corresponding factor  $f (= 1 - Q^+/Q^-)$  is not low enough to cool down the disk, (in [1], it is indicated that  $\dot{m}/\alpha^2$  is a good indication of the cooling efficiency of the hot flow), where  $Q^+$  and  $Q^-$  are the heat gain and heat loss due to viscosity of the disk.

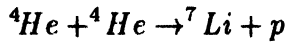
We have studied a large region of parameter space with  $0.0001 \lesssim \alpha \lesssim 1$ ,  $0.001 \lesssim \dot{m} \lesssim 100$ ,  $0.01 \lesssim \beta \lesssim 1$ ,  $4/3 \lesssim \gamma \lesssim 5/3$ . We study a case with a standing shock as well. In selecting the reaction network we kept in mind the fact that hotter flows may produce heavier elements through triple- $\alpha$  and rapid proton and  $\alpha$  capture processes. Furthermore due to photo-dissociation significant neutrons may be produced and there is a possibility of production of neutron rich isotopes. Thus, we consider sufficient number of isotopes on either side of the stability line. The network thus contains protons, neutrons, till  $^{72}\text{Ge}$  - altogether 255 nuclear species. The standard reaction rates were taken [6].

### 3. Results

Here we present a typical case containing a shock wave in the advective region [6]. We express the length in the unit of one Schwarzschild radius which is

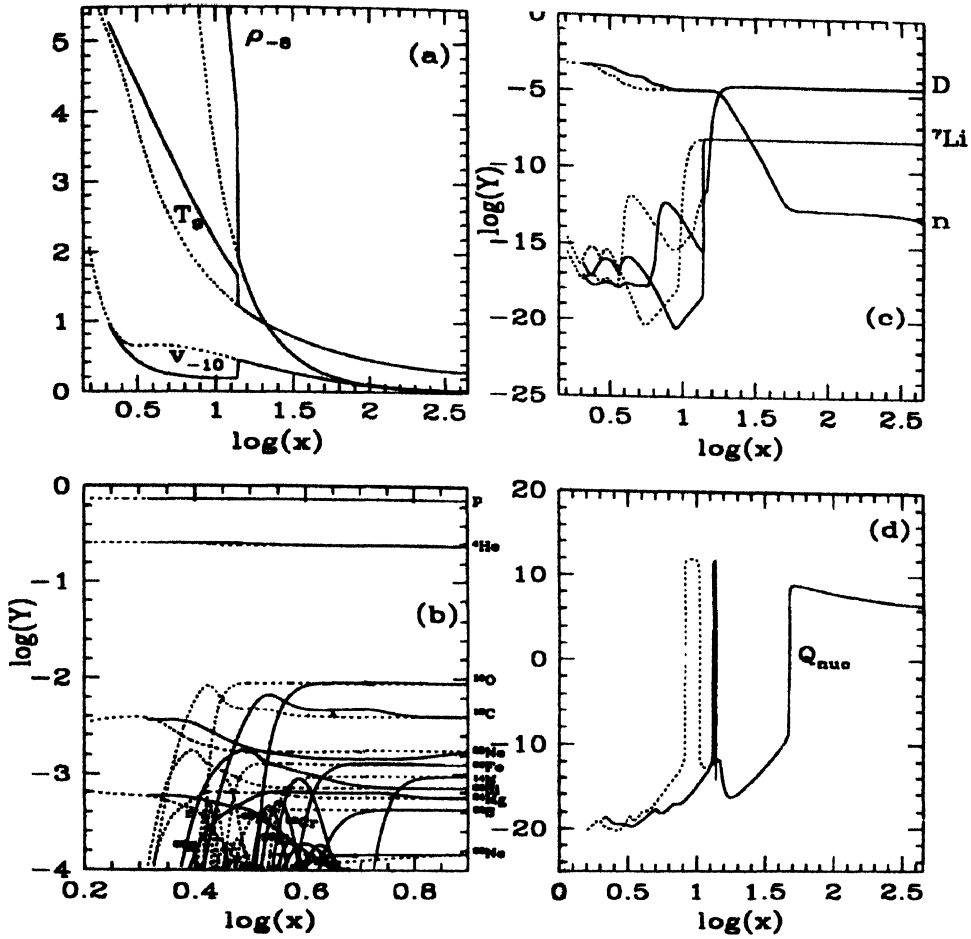
$\frac{2GM}{c^2}$  where  $M$  is the mass of the black hole, velocity is expressed in the unit of velocity of light  $c$  and the unit of time is  $\frac{2GM}{c^3}$ . We use the mass of the black hole  $M/M_\odot = 10$  ( $M_\odot$  = solar mass),  $\Pi$ -stress viscosity parameter  $\alpha_\Pi = 0.05$ , the location of the inner sonic point  $x_{in} = 2.8695$ , the value of the specific angular momentum at the inner edge of the black hole  $\lambda_{in} = 1.6$ , the polytropic index  $\gamma = 4/3$  as free parameters. The net accretion rate  $\dot{m} = 1$  in the unit of Eddington rate, cooling factor due to Comptonization  $\beta = 0.03$ ,  $x_K = 481$ . The proton temperature (in the unit of  $10^9$ ), velocity distribution (in the units of  $10^{10}$  cm sec $^{-1}$ ), density distribution (in the unit of  $2 \times 10^{-8}$  gm cm $^{-3}$ ) are shown in Fig. 1(a).

In Fig. 1b, we show composition changes close to the black hole both for the shock-free branch (dotted curves) and the shocked branch of the solution (solid curves). Only prominent elements are plotted. The difference between the shocked and the shock-free cases is that, in the shock case the similar burning takes place farther away from the black hole because of much higher temperature in the post-shock region. A significant amount of the neutron (with a final abundance of  $Y_n \sim 10^{-3}$ ) is produced due to photo-dissociation process. Note that closer to the black hole,  $^{12}\text{C}$ ,  $^{16}\text{O}$ ,  $^{24}\text{Mg}$  and  $^{28}\text{Si}$  are all destroyed completely. Among the new species which are formed closer to the black hole are  $^{30}\text{Si}$ ,  $^{46}\text{Ti}$ ,  $^{50}\text{Cr}$ . Note that the final abundance of  $^{20}\text{Ne}$  is significantly higher than the initial value. Thus a significant metallicity could be supplied by winds from the centrifugal barrier. In Fig. 1c we show the change of abundance of neutron ( $n$ ), deuterium ( $D$ ) and lithium ( $^7\text{Li}$ ). It is noted that near black hole a significant amount of neutron is formed although initially neutron abundance was almost zero. Also  $D$  and  $^7\text{Li}$  are totally burnt out near black hole which is against the major claim of Yi & Narayan [13] which found significant lithium in the disk. It is true that due to spallation reaction, i.e.,



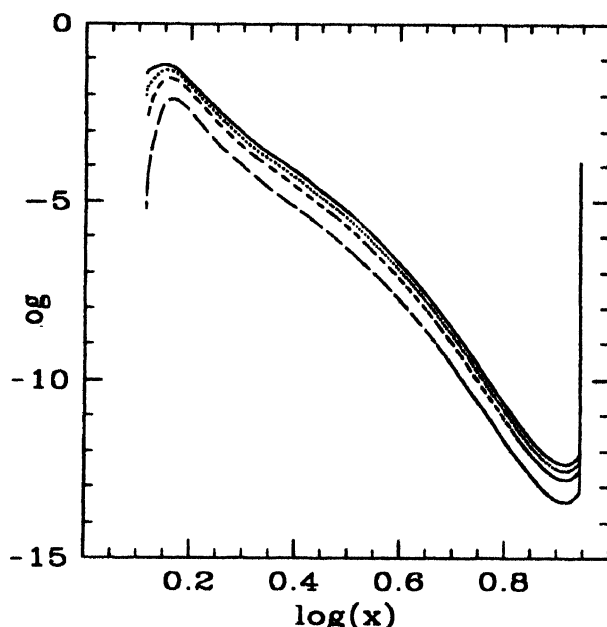
$^7\text{Li}$  may be formed in the disk but due to photo-dissociation in high temperature all  $^4\text{He}$  are burnt out before forming  $^7\text{Li}$  i.e. the formation rate of  $^4\text{He}$  from  $D$  is much slower than the burning rate of it. Yi & Narayan [13] do not include the possibility of photo-dissociation in the hot disk.

In Fig. 1d, we show nuclear energy release/absorption for the flow in units of erg sec $^{-1}$  gm $^{-1}$ . Solid curve represents the nuclear energy release/absorption for the shocked flow and the dotted curve is that for unstable shock-free flow. As matter leaves the Keplerian region, the rapid proton capture such as,  $p + ^{18}\text{O} \rightarrow ^{15}\text{N} + ^4\text{He}$  etc., burn hydrogen and releases energy to the disk. At around  $x = 50$ ,  $D \rightarrow n + p$  dissociates  $D$  and the endothermic reaction causes the nuclear energy release to become 'negative', i.e., a huge amount of energy is absorbed from the disk. At around  $x = 15$  the energy release is again dominated by the original processes because no deuterium is left to burn. Due to excessive temperature, immediately  $^3\text{He}$  breaks down into deuterium and



**Figure 1.** Variation of (a) proton temperature ( $T_9$ ), radial velocity  $v_{10}$  and density distribution  $\rho_{-8}$  (b) matter abundance  $Y$  in logarithmic scale (c) neutron, deuterium and lithium abundance  $Y$  in logarithmic scale and (d) nuclear energy release and absorption as a functions of logarithmic radial distance  $x$ . See text for parameters. Solutions in the stable branch with shocks are solid curves and those without the shock are dotted in (a-d). At the shock, temperature and density rise and velocity lower significantly and cause a significant change in abundance even farther out. Shock induced winds may cause substantial contamination of the galactic composition when parameters are chosen from these regions [6].

through dissociation of  $D$  again a huge amount of energy is absorbed from the disk. It is noted that energy absorption due to photo-dissociation as well as the magnitude of the energy release due to proton capture process and that due to



**Figure 2.** The convergence of the neutron abundance through successive iterations in a very hot advective disk. From bottom to top curves 1st, 4th, 7th and 11th iteration results are shown. A neutron torus with a significant abundance is formed in this case [15].

viscous dissipation ( $Q^+$ ) are *very* similar (save the region where endothermic reactions dominate). This suggests that even with nuclear reactions, at least some part of the advective disk may be perfectly stable.

We now present another interesting case where lower accretion rate ( $\dot{m} = 0.01$ ) but higher viscosity (0.2) were used and the efficiency of cooling is not 100% ( $f = 0.1$ ). That means that the temperature of the flow is high ( $\beta = 0.1$ , maximum temperature  $T_9^{max} = 11$ ). In this case  $x_K = 8.8$ , if the high viscosity is due to stochastic magnetic field, protons would be drifted towards the black hole due to magnetic viscosity, but the neutrons will not be drifted [13] till they decay. This principle has been used to do the simulation in this case. The modified composition in one sweep is allowed to interact with freshly accreting matter with the understanding that the accumulated neutrons do not drift radially. After few iterations or sweeps the steady distribution of the composition may be achieved. Figure 2 shows the neutron distributions in iteration numbers 1, 4, 7 & 11 respectively (from bottom to top curves) in the advective region. The formation of a 'neutron torus' is very apparent in this result and generally in all the hot advective flows. In 1987 Hogan &

Applegate [14] showed that formation of neutron torus is possible with high accretion rate. But high accretion rate means high rate of photon to dump into sub-Keplerian region and high rate of inverse Compton process through which matter cool down, that is why photo-dissociation will be less prominent. Also formation of neutron is possible through the photo-dissociation of deuterium in the hot disk which is physically possible prominently in our parameter region, where neutron torus is formed. Details are in Chakrabarti & Mukhopadhyay [15].

#### 4. Discussions and conclusions

In this paper, we have explored the possibility of nuclear reactions in advective accretion flows around black holes. Temperature in this region is controlled by the efficiencies of bremsstrahlung and Comptonization processes [2, 7]. For a higher Keplerian rate and higher viscosity, the inner edge of the Keplerian component comes closer to the black hole and the advective region becomes cooler [2, 9]. However, as the viscosity is decreased, the inner edge of the Keplerian component moves away and the Compton cooling becomes less efficient.

The composition changes especially in the centrifugal pressure supported denser region, where matter is hotter and slowly moving. Since centrifugal pressure supported region can be treated as an effective surface of the black hole which may generate winds and outflows in the same way as the stellar surface, one could envisage that the winds produced in this region would carry away modified composition [16-18]. In very hot disks, a significant amount of free neutrons are produced which, while coming out through winds may recombine with outflowing protons at a cooler environment to possibly form deuteriums. A few related questions have been asked lately: Can lithium in the universe be produced in black hole accretion [12,19]? We believe that this is not possible. When the full network is used we find that the hotter disks where spallation would have been important also heliums photo-dissociate into deuteriums and then to protons and neutrons before any significant production of lithiums. Another question is: Could the metallicity of the galaxy be explained, at least partially, by nuclear reactions? We believe that this is quite possible. Details are in [6].

Another important thing which we find that in the case of hot inflows formation of neutron tori is a very distinct possibility [15]. Presence of a neutron torus around a black hole would help the formation of neutron rich species as well, a process hitherto attributed to the supernovae explosions only. It can also help production of Li on the companion star surface (see [6] and references therein).

The advective disks as we know today do not perfectly match with a Keplerian disk. The shear, i.e.,  $d\Omega/dx$  is always very small in the advective flow compared to that of a Keplerian disk near the outer boundary of the advective

region. Thus some improvements of the disk model at the transition region is needed. Since major reactions are closer to the black hole, we believe that such modifications of the model would not change our conclusions. The neutrino luminosity in a steady disk is generally very small compared to the photon luminosity [6], but occasionally, it is seen to be very high. In these cases, we predict that the disk would be unstable. Neutrino luminosity from a cool advective disk is low.

In all the cases, even when the nuclear composition changes are not very significant, we note that the nuclear energy release due to exothermic reactions or absorption of energy due to endothermic reactions is of the same order as the gravitational binding energy release. Like the energy release due to viscous processes, nuclear energy release strongly depends on temperatures. This additional energy source or sink may destabilize the flow [6].

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